Coupled Atmospheric and Oceanic Effects on Mixed Layer Depth Variability

William A. Swick

Operational Oceanography and Meteorology, NPS - Monterey

1. Introduction

The ideal ocean mixed layer is a homogeneous fully turbulent region of the upper ocean that is bounded above by the air-sea interface, and below by a turbulent entrainment zone. This entrainment zone is where temperature and salinity undergo jumps which give rise to strong fluxes of temperature and salinity. Below this entrainment zone is stratified water that increases in density with depth (Garwood 1977).

The observed mixed layer captured in a 29-hour Conductivity, Temperature and Depth (CTD) timeseries in the Monterey Canyon was more variable than the ideal case.

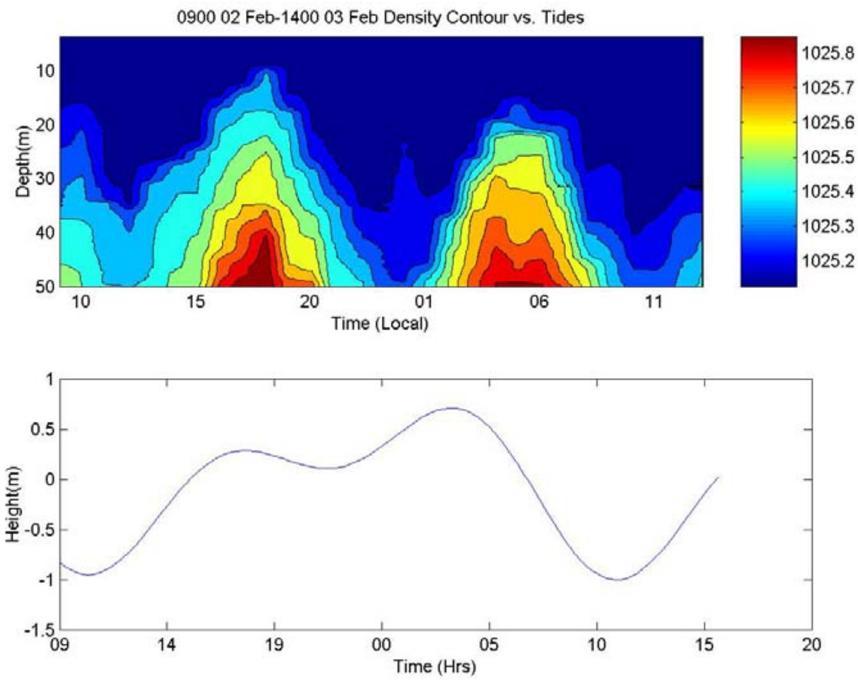


Figure (1): Mixed layer variability and Surface Tides

The role of air-sea influences on the real world variability of the oceanic mixed layer depth will be explained in the paper.

2. Data

A 29-hour timeseries (0900L, 02 Feb 03 to 1400L 03 Feb 03) was taken in Monterey Canyon at Station S2 (36.79248N 121.84222W). Each cast was processed to a depth of 50 m with a depth resolution of 1 cm. The ships underway data acquisition system (UDAS) recorded: Wind Speed, Air Temperature, Humidity, Solar Radiation, and Sea Surface Temperature. The PC Tides Model was run for location S2 for the duration of the timeseries. To get an estimate of precipitation amounts, due to the intermittent rain squalls spanning the measurement period, data from the following six rain gauges where used: Del Monte Beach, R7, R30, Fort Ord #1, Fort Ord Profiler, and Watsonville.

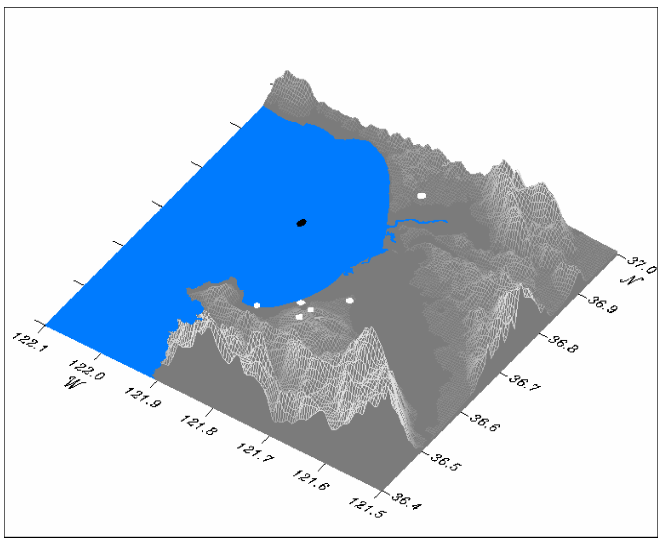


Figure (2): CTD Timeseries location (black) and rain gauge locations (white)

3. Theory

Mixed layer dynamics are strongly coupled. Understanding how the mixed layer will shallow or deepen is the sum of two dependent components: vertical entrainment velocity and the vertical motion of the ocean at the mixed layer depth.

$$\frac{dh}{dt} = we + W\big|_{-h} \tag{1}$$

Vertical motion at the mixed layer depth is entirely ocean driven. In most regions vertical motion constitutes a substantial fraction of the total mixed layer variability. However, to neglect entrainment based on this would be an error. The atmosphere and ocean are strongly coupled, neither component can be neglected.

$$we = \frac{\left(c_1 u_*^3 + c_2 w_*^3\right)}{\alpha gh\Delta T - \beta gh\Delta S} \tag{2}$$

The Krauss and Turner (1967) equation for entrainment emphasizes the role of turbulence in mixed layer dynamics. The turbulent energy produced at the sea surface is transferred down to the mixed layer depth where it erodes the temperature and salinity jumps, cooling and/or deepening the mixed layer. Turbulence at the air-sea interface may be produced by forced convection (u_*) due to wind stresses and/or free-convection (w_*). Free convection depends upon the integral of the buoyancy flux across the mixed layer and thereby is dependent on the temperature and salinity fluxes at the air-sea interface.

$$u_*{}^2 = \frac{\rho_{\text{air}}}{\rho_{\text{ocean}}} C_D (U_{10})^2 \tag{3}$$

$$w_*{}^3 = \left[\alpha g \left(\frac{Q_0}{\rho c_p} \right) - \beta g (P)(S) \right] h \tag{4}$$

where P is precipitation rate in (m/s) and the net downward heat flux is:

$$Q_0 = -Q_{solar} + Q_{backradiation} + Q_{latentheat} + Q_{sensibleheat} \tag{5}$$

A high albedo value of 0.3 was chosen for the sea surface and multiplied by Q_{solar} to account for $Q_{backradiation}$ which was not measured at the ship. This estimate of Qo was sufficient for this study because small heating errors have a relatively small effect compared to the wind and/or precipitation effects on entrainment.

The entrainment velocity (*we*) drives the overall oceanic heat and salinity flux mixing underlying water from below cooling and deepening the mixed layer. Entrainment must be positive or zero, negative entrainment is not physical because water cannot be unmixed.

This introduces the idea that the mixed layer has two regimes. A deepening regime (2) where entrainment is positive and a shallowing regime (6), where the wind stress at the sea surface ($u_\star$ is always>0) is exactly balanced by buoyant damping ($w_\star$< 0). Buoyant damping is due to heating and/or precipitation at the surface which produces a stabilizing effect on the mixed layer.

$$c_1 u_*^3 = c_2 \left[\alpha g \left(\frac{Q_0}{\rho c_p} \right) - \beta g (P)(S) \right] h \tag{6}$$

From equation (6) it can be seen that atmospheric forcing governs whether the air-sea system is in a deepening or a shallowing regime. Because wind stress can only add turbulence into the mixed layer the regime reversals are due to the total amount of buoyancy flux or damping across the mixed layer. Further, in a shallowing regime the mixed layer does not "feel" the underlying ocean. The mixed layer depth is determined solely by atmospheric forcing due to the overall energy balance of wind, heat and precipitation.

4. Mixed Layer Entrainment Model

A one-dimensional mixed layer turbulent kinetic energy (TKE) budget model based on Garwood's NPS mixed layer model for deep convection (Garwood 1991) was written in MATLAB. It consisted of a system of seven equations derived by vertically integrating the budgets for heat, momentum, salinity, and turbulent kinetic energy between the air-sea interface and the base of the turbulent mixed layer. This system was solved using MATLAB ordinary differential equation solver ODE45. ODE45 is a *one-step* solver in computing y(t), it needs only the solution at the immediately preceding time point.

The model examined the energetics of free convection and force convection by calculating the total TKE transferred down to the entrainment zone. This available energy does work entraining cold, salty water and deepening the mixed layer. The TKE equation is:

$$\frac{\partial}{\partial t}\left(\frac{\overline{u'^2}+\overline{v'^2}+\overline{w'^2}}{2}\right)=-\left[\overline{u'w'}\frac{\partial U}{\partial z}+\overline{v'w'}\frac{\partial V}{\partial z}\right]+\overline{b'w'}-\frac{\partial}{\partial z}\left[\overline{w'\left(\frac{u'^2+v'^2+w'^2}{2}+\frac{p}{\rho_0}\right)}\right]-\varepsilon\approx 0 \tag{7}$$

The term on the left-hand side is total TKE per unit mass. The four terms on the right-hand side are: shear production of horizontal turbulence generated by the wind stress, buoyancy flux production (+) or damping (-), vertical diffusion of TKE by turbulent and pressure transport, and viscous dissipation.

5. Analysis

The Figure (1) is a timeseries of density contours computed using the temperature and salinity measurements from the CTD casts at S2 and the predicted tides for the same period. From the large changes in depth of the isopycnals it is evident that there is an internal wave propagating through the water column. The wave amplitude is ~20m at the mixed layer depth and there is an observed phase lag of 6.5 hours which is in agreement with previous studies conducted in the Monterey Canyon (Rosenfeld 1999). Air-sea coupling in mixed layer dynamics prevents assuming atmospheric effects to be negligible despite the large amplitude of the internal wave.

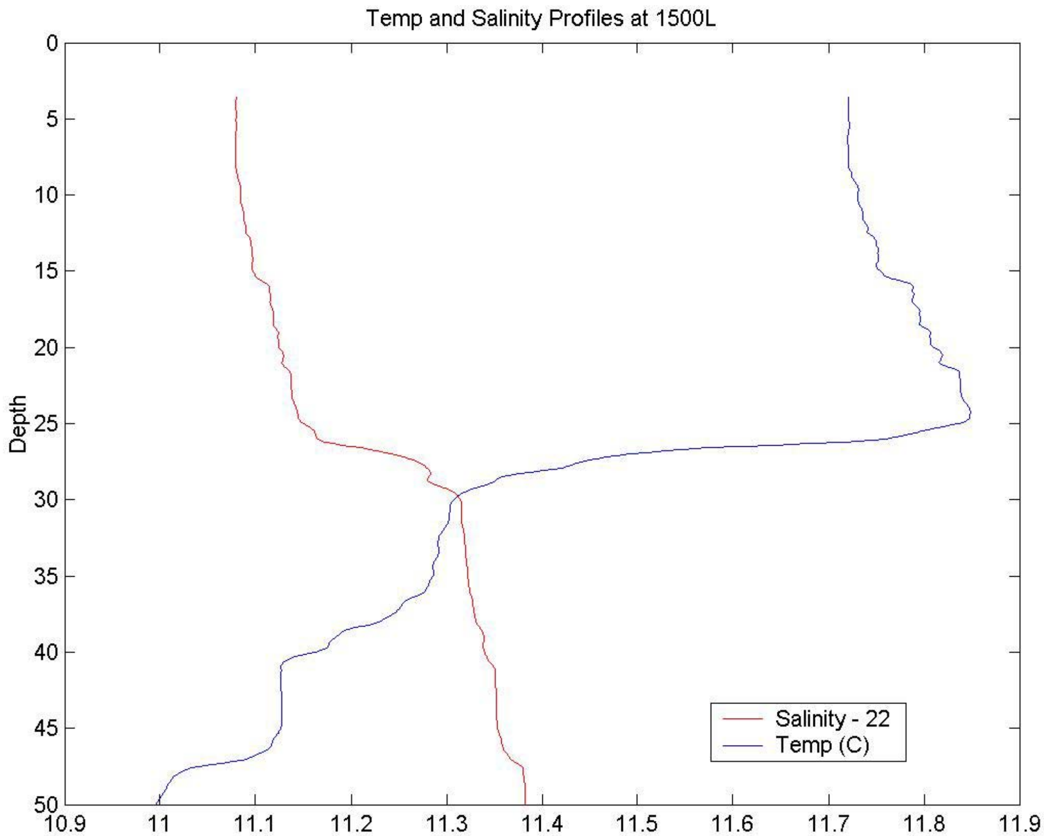


Figure (3): 1500L temperature and salinity profile

Figure (3) shows the mixed layer depth to be 16 m. There is a temperature inversion, which is balanced by a strongly stable salinity profile. Calculations show that the layer is stable and dominated by strong salinity stratification.

$$\Delta b = \alpha g \Delta T - \beta g \Delta S \tag{8}$$

$$\frac{\beta g \Delta S}{\alpha g \Delta T} = \frac{.0076(.04)}{.0017(.07)} = 2.56 \tag{9}$$

The salinity stratification is due to the intermittent rainsqualls which occurred throughout the period of measurement. The effect of the rainsqualls was to shallow the mixed layer by buoyant damping. This shallowing is observed to be independent of the underlying internal wave.

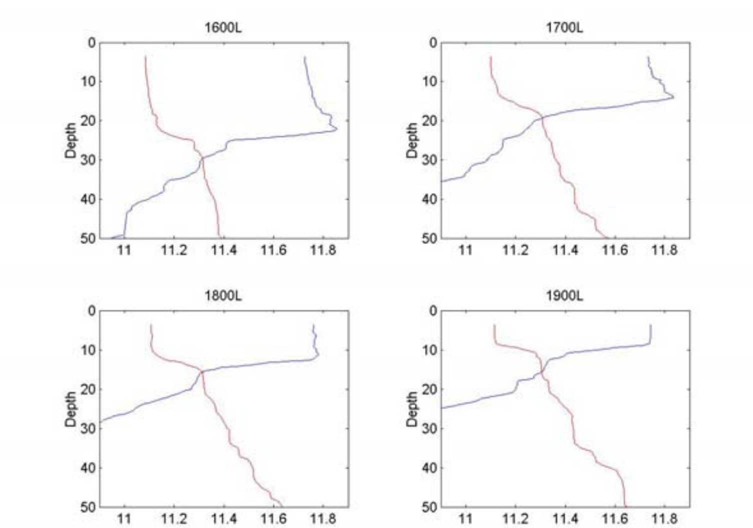


Figure (4): Mixed layer shallowing over a four hour period

The equation for integrated buoyancy flux (4) demonstrates that the precipitation rate is providing more buoyant damping than both the wind stress and surface cooling are adding to turbulence and free convection. With estimates of wind stress and net surface heat flux, a precipitation rate at which the mixed layer remains constant can be calculated.

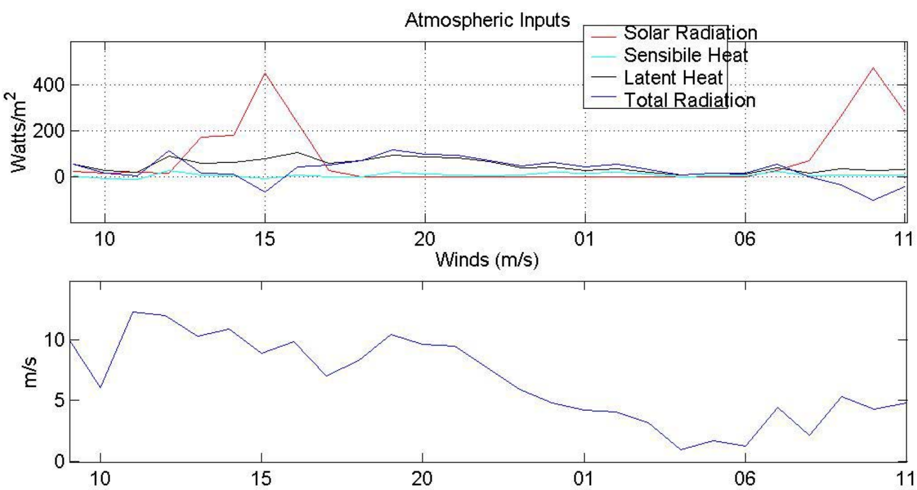


Figure (5): shows the measured wind and heating during the CTD timeseries

Based on Figure (4) wind speed values of 5 m/s and 25 W/m/m of cooling where used to calculate a minimum precipitation rate which would make ($\frac{dh}{dt}=0$). A rate of 0.37 cm/hr was calculated which agrees very well with the observe rainfall at the six land based stations.

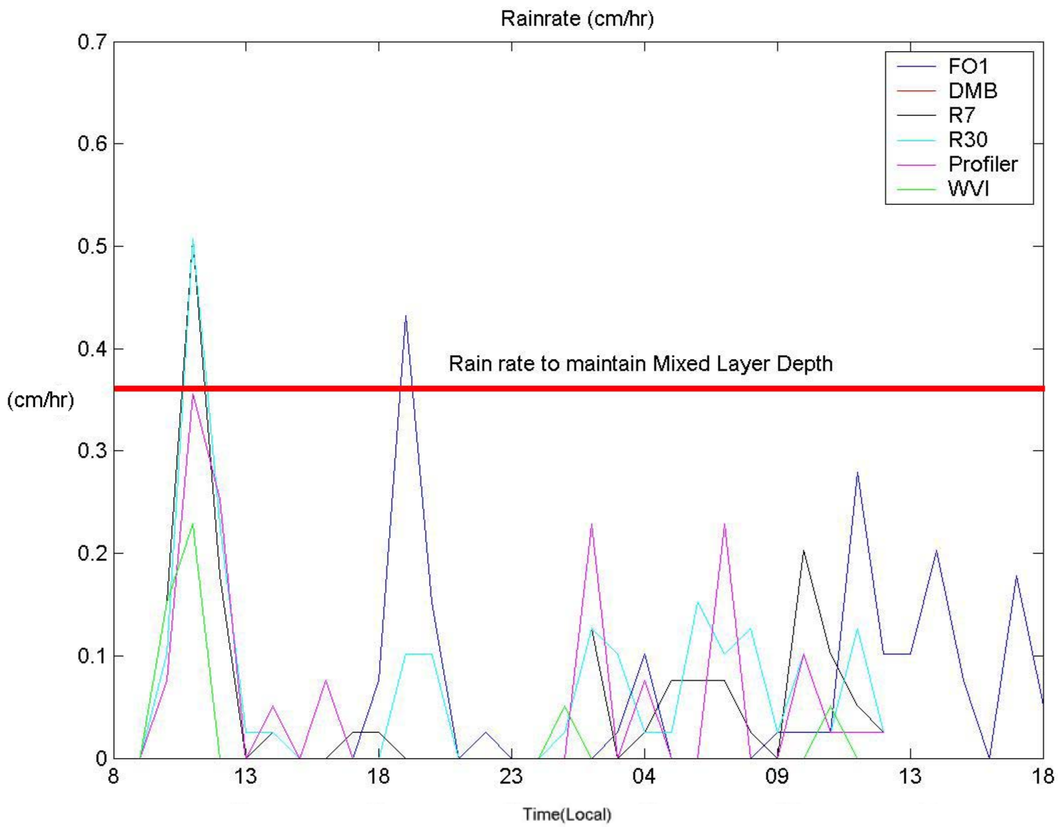


Figure (6): Precipitation rate of 0.37 cm/hr agrees with observed rainfall

A rain rate greater than 0.37 cm/hr implies a shallowing regime and a rain rate less then 0.37 cm/hr implies a deepening regime.

The most intense rainsqualls occurred on 02 Feb before 1900L. After 1900L, the rain weakened and the rain rate minimum was not met. Based on the calculated minimum we expect to enter a deepening regime due to the wind and surface cooling overcoming the stabilizing effect of the precipitation.

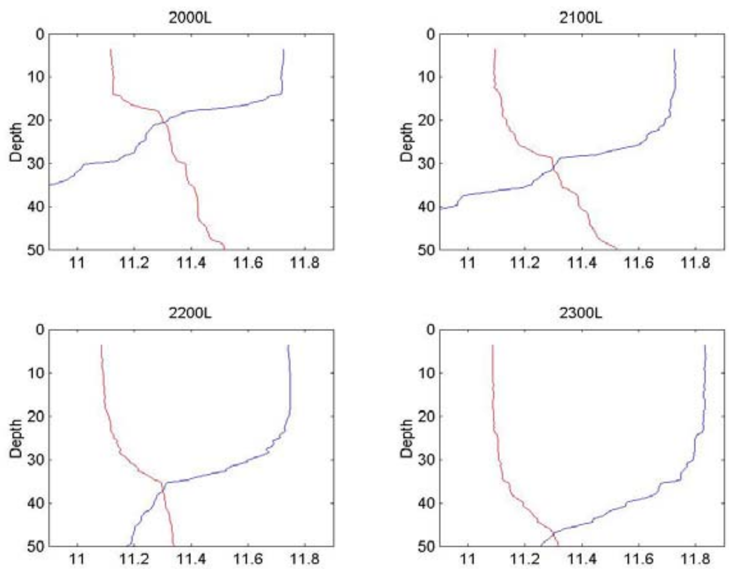


Figure (7): Observed Deepening

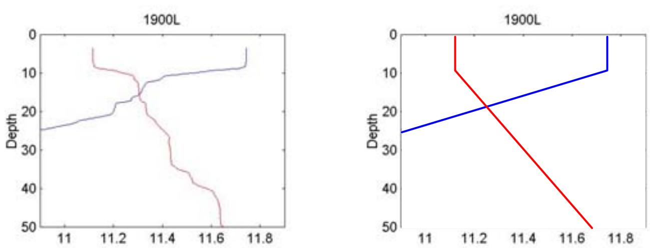
In Figure (6) we observe this deepening occurring very rapidly due to the entrainment and vertical motion of the Monterey Canyon internal tide acting in concert.

The mixed layer model for deepening regimes was run to compare the relative effects of deepening due to the coupled mixed layer system and the deepening due to the internal wave only.

To model entrainment the mixed layer was simplified to a two layer ocean with the following initial conditions:

Initial Conditions:
Model duration = 0.25 (days)
Mixed Layer Depth = 900 (cm)
Temperature_{sfc} = 11.75 (C)
Salinity_{sfc} = 33.13
Salinity Gradient = -0.0004 (dS/dz)
Temperature Gradient= 0.000133 (dT/dz)

Forcing:
Q = 25 (W/m/m)
Precipitation = 0.0 (run#1) and 0.12 (run#2) (cm/hr)
Wind Speed = 5 (m/s)



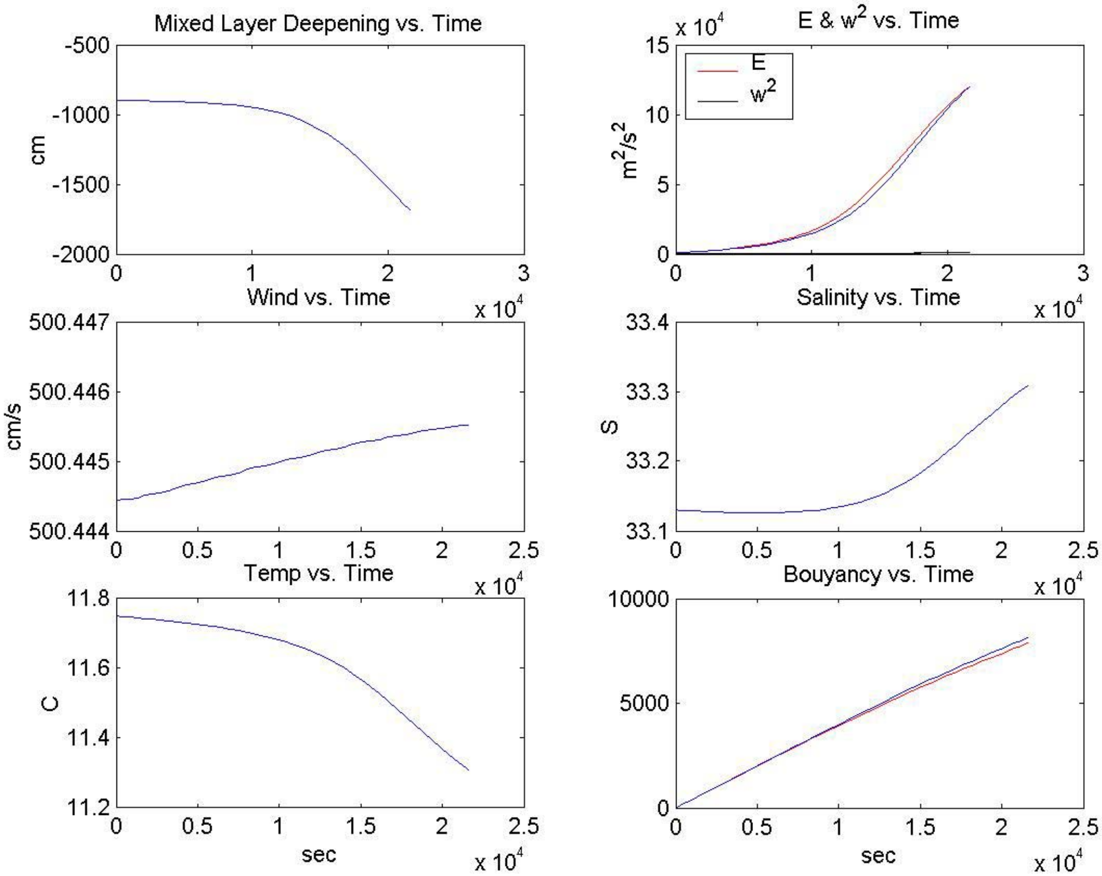
Figure(8): Observed T-S Profile and simplified two-layer ocean model profile

The internal tide was assumed to be a semi-diurnal wave with an amplitude of 20m at a depth of 35m ($A_{35} = 20m$). The amplitude decreased linearly towards the surface as observed in the ITEX1 experiment (Rosenfeld 1999).

$$W\Big|_{-h} = \frac{h(t)}{35} \times A_{35} \times -\sin(\omega t) \tag{8}$$

$$\omega = \frac{2\pi}{12*3600} = semidiurnal\_tide \tag{9}$$

The model results, Figure (9), supported the precipitation rate minimum calculation, by confirming the mixed layer was in a deepening regime. Two precipitation rates (0 cm/hr and 0.12 cm/hr) were run in order to compare the relative effect. No perceivable deepening effect was observed as a result of this precipitation change. Apparently the wind speed of 5 m/s is generating enough turbulence to dominate the buoyant damping caused by the precipitation. Total deepening due to entrainment was significant; 7 m in six hours. Figure 10 shows deepening of the mixed layer due to internal tide only and the combined effects of entrainment and the internal tide. The entrainment effects are shown to be important during both regimes.



Figure(9): Model results supported precipitation rate minimum calculations

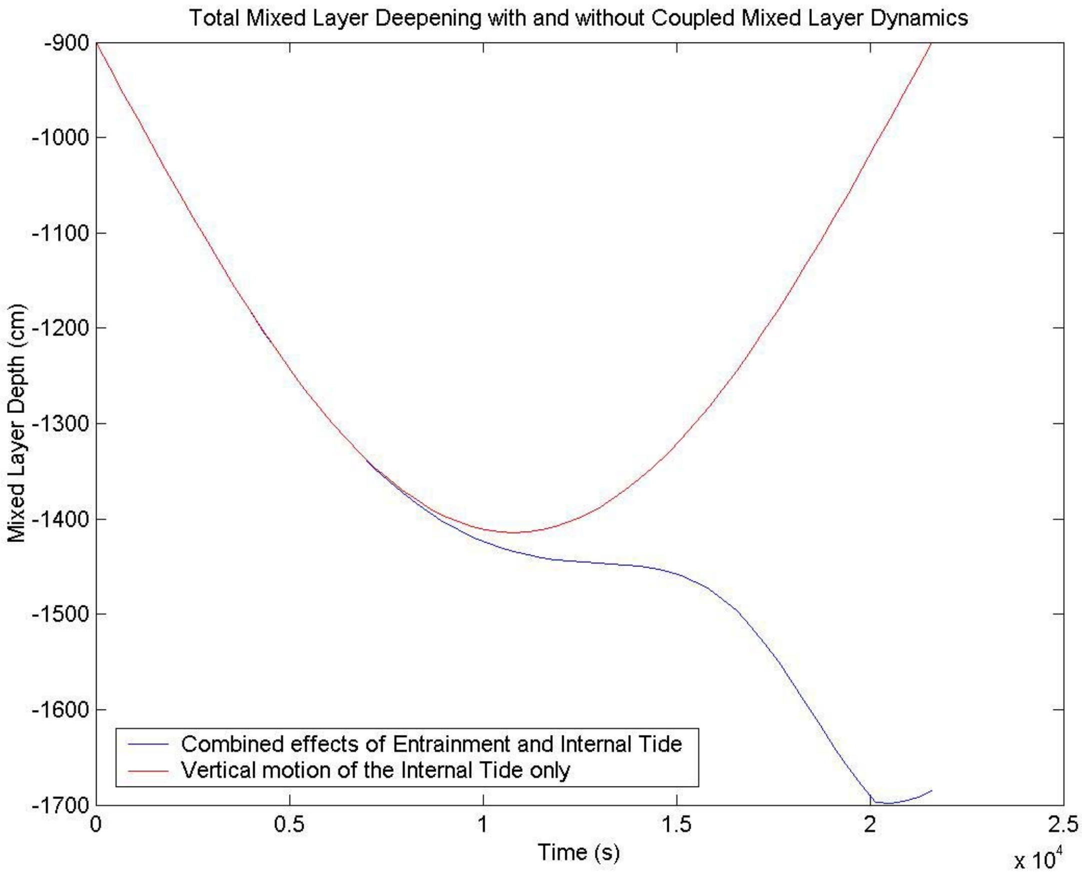


Figure 10 Air-Sea Coupling in the Deepening Regime

6. Conclusion

There is no single factor that is most important in determining the mixed layer variability. Dynamics of the mixed layer are a result of the air-sea system interaction as a whole. This project illustrated the complexity of these interactions, and the short time scale upon which the mixed layer depth responds to small changes in forcing conditions. The atmosphere governs the regime type, deepening or shallowing. The ocean internal wave is also a large contributor in both regimes. Understanding limits and the relative importance of the different contributors to the heat, momentum, salinity, and TKE budgets is vital to the accurate prediction of the mixed layer depth.

"We are all something, but none of us are everything."
(Philosopher, Mathematician, and Physicist: Blaise Pascal)

REFERENCES

Garwood, R.W., Jr. An oceanic mixed layer model capable of simulating cyclic states. *J. Phys. Oceanography*, 7, 455-471, 1977.

Garwood, R.W., Jr. Enhancements to deep turbulent entrainment. In *Deep Convection and Deep Water Formation in the Ocean*, Ed. by P. C. Chu and J. C. Gascard, Elsevier, 189-205, 1991.

Kraus, E.B. and J.S. Turner. A one-dimensional model of the seasonal thermocline. *Tellus*, 19, 98-105, 1967.

Rosenfeld, L.K., J.D. Paduan, E.T. Petruncio, and J.E. Goncalves, 1999: Numerical simulations and observations of the internal tide in a submarine canyon. *Proceedings, 'Aha Huliko'a Hawaiian Winter Workshop*, University of Hawaii at Manoa, January 19-22